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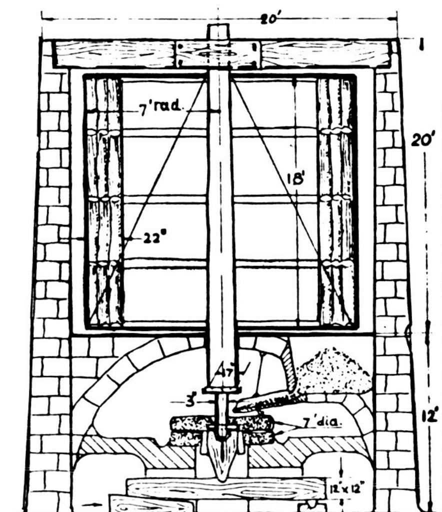
WIND ENERGY DEVELOPMENTS IN THE 20TH CENTURY

by DONALD J. VARGO



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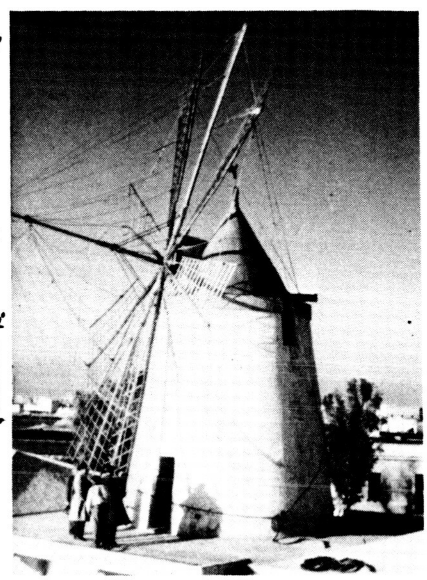
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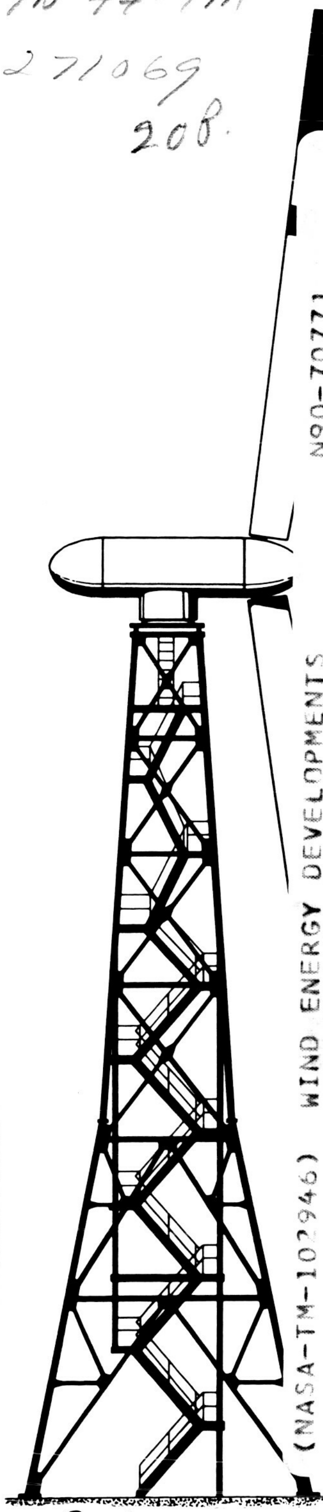
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LEWIS RESEARCH CENTER CLEVELAND, OHIO

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Donald J. Vargo

Technology Utilization and Public Affairs Office
LEWIS RESEARCH CENTER *Cleveland, Ohio*
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Historically, wind-driven energy conversion devices can be considered as one of man's truly basic machines. Simple vertical-axis wind machines were in existence in Persia several hundred years before the time of Christ (refs. 1 and 2). These primitive wind machines stayed the same until the 12th century, when almost simultaneously in France and England the horizontal-axis or Dutch-type windmill made its appearance (fig. 1). Dutch settlers brought the windmill to America in the mid 1700's (ref. 3). These windmills typically ground grain and pumped water. Through the years, the design of these windmills changed only superficially.

In 1890, the first of the modern windmills for producing electricity was designed, built, and put into service in Denmark (refs. 1 and 4). By 1908 several hundred wind power stations producing from 5 to 25 kilowatts dotted the Danish landscape. Wind machines played a significant role in rural America until the 1930's, when the Rural Electrification Act (REA) provided cheap electricity to the farmers. The remnants of many of these early wind machines are still visible in various parts of the country. All these machines were relatively small and did

Figure 1. - Typical Dutch type windmill.

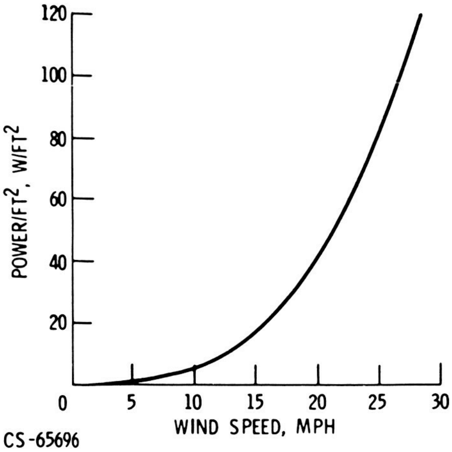

Figure 2. - Power density of the wind.

not produce much power.

The variation of the power of the wind with wind speed is presented in figure 2. Note that at a wind speed of 13 mph, approximately 10 watts of power is contained in each square foot of wind area (where area is taken perpendicular to the wind direction). This represents the theoretical power available. The laws of nature limit power transmission of ideal propellers to 59.3 percent. Because of the losses of a real propeller, gearing, and generator, the power that could actually be obtained from 1 square foot of this 13-mph wind would be 3 to 3.5 watts.

In the 20th century, the search for power led several countries to attempt to tap this widespread source of "free" energy. For the first time comparatively large wind machines were constructed and tested.

One of the first of the large experimental machines was the 100-kilowatt wind turbine that was built in 1931 by the Russians (fig. 3). It was located at Balaclava near Yalta on the Black Sea (refs. 5 to 7). The rotor was 100 feet in diameter, and the tower was 100 feet high. Maximum rated power, 100 kilowatts, was obtained at wind speeds in excess of 24.6 mph. The average wind speed at the site was 15 mph. The rotor drove a 100-kilowatt, 200-volt induction generator, which was connected by a 6300-volt line to a 20-megawatt steam power station located in Sevastopol some 20 miles away. Although this wind machine was very primitive, that is, the blade surface was roofing metal and the main gears were made of wood, one year the plant did achieve an output of 279,000 kilowatt-hours. This gave a power utilization yield (actual power output divided by total possible power output) of 32 percent. The generator and controls were located in the housing on top of the tower. Regulation was accomplished by pitch control of the blade. The wind thrust was absorbed by the inclined strut. The ground portion of this strut rested on a carriage

Figure 3. - 100 kW Russian wind turbine.

which sat on a circular track. The carriage was automatically driven to keep the rotor facing into the wind. In addition to this machine, many smaller machines have been installed in Russia to supply power to agricultural communities.

The largest wind machine to date (1250 kW) was started in 1934 when an engineer, Palmer C. Putnam, began to consider wind-driven generators for reducing the cost of electricity at his Cape Cod home (refs. 5 and 8 to 10). In 1939, Putnam presented his ideas and the results of his preliminary work to the S. Morgan Smith Company of York, Pennsylvania. The company agreed to fund a wind energy project, and the Smith-Putnam wind turbine experiment was born. The wind machine was to be connected to the existing system of the Central Vermont Public Service Corporation. Out of some 50 Vermont sites considered, a 2000-foot hill, Grandpa's Knob, located in Rutland, was selected. A number of engineers from several universities participated in the project. On August 29, 1941, less than 2 years after the original meeting, the blades were rotated for the first time.

The Smith-Putnam machine (fig. 4) was physically the largest wind machine ever built and tested. The tower was 110 feet high, while the rotor was 175 feet in diameter and had an 11-foot, 4-inch chord. Each blade weighed 8 tons and consisted of stainless steel ribs covered by a stainless steel skin. The blade pitch was adjustable, so that a constant rotor speed of 28.7 rpm could be maintained. This rotational speed was maintained in wind speeds as high as 70 to 75 mph. At higher wind speeds,

Figure 4. - 1250 kW Smith-Putnam machine.

the blades were feathered, and the machine was brought to a stop. The rotor turned an ac synchronous generator that produced 1250 kilowatts of power at wind speeds greater than 30 mph. This power was fed into the power company network.

Shortly after the system had undergone its initial checkout and was brought on line, a main bearing failed. Since World War II was in progress and this project had low priority, it took several years to obtain a new main bearing. The new bearing was installed early in 1945. Following the installation, the machine was operated only a few months when an overstressed blade failed. Total intermittent running time achieved was 1100 hours. The project was reviewed, and although considered to have been a technical success, was not considered to have been an economic success. The original installation cost data indicated that additional machines in small quantities would have cost approximately $190 per kilowatt. The target price in 1945 was $125 per kilowatt. The project was stopped, and the wind machine was dismantled.

The technical results of the Smith-Putnam wind turbine caused Percy H. Thomas, an engineer with the Federal Power Commission, to spend approximately 10 years in a detailed analysis of wind power generation of electricity (refs. 10 and 11). Mr. Thomas, using largely the economic data from the Grandpa's Knob operation, initially concluded that a 5000- to 10,000-kilowatt wind-driven machine was necessary for economic feasibility. He designed two large machines, one for 6500 kilowatts and the other for 7500 kilowatts.

The 6500-kilowatt machine is shown in figure 5. In 1951 the Federal Power Commission tried to interest Congress in funding a prototype of this machine. Because the Korean War was in progress, the project was not funded and was subsequently cancelled. Some details of the proposed system were as follows: The tower height was to be 475 feet, and each of the rotors 200 feet in diameter. The rotors were to drive dc generators which would produce 6500 kilowatts at wind speeds greater than 28 mph. The dc power was to feed to a dc-to-ac synchronous converter, which would supply the electrical network. All generating equipment was to be housed at the top of the tower. Mr. Thomas estimated the capital costs for this machine as $75 per kilowatt.

The English also had a fairly extensive wind energy program from 1945 to 1960 (ref. 7). One machine, shown in figure 6, was the Enfield-Andreau wind turbine. This machine

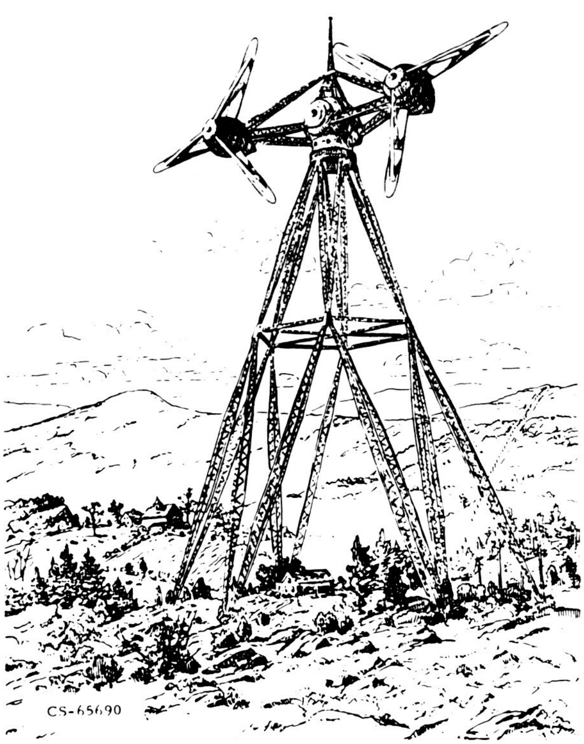

Figure 5. - Proposed 6500 kW Percy Thomas twin wheel turbine.

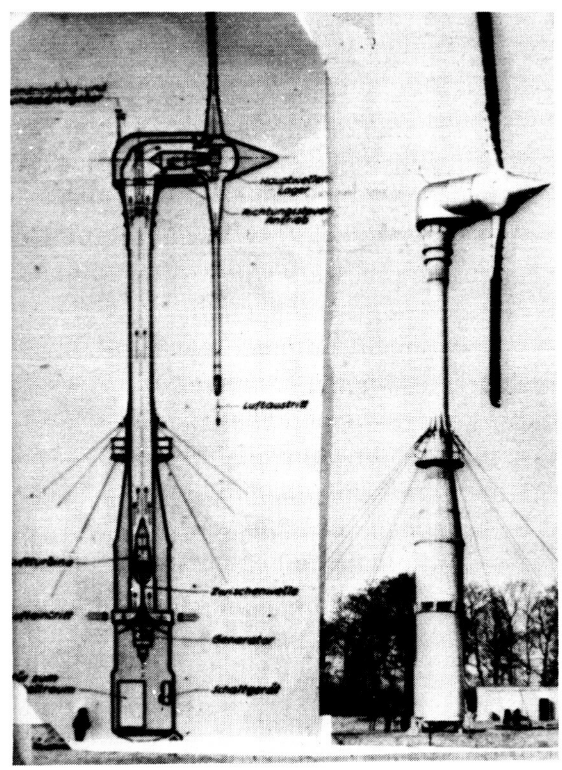

Figure 6. - 100 kW Enfield-Andreau machine.

was built in England and set up at St. Albans in the early 1950's. It was designed to put out 100 kilowatts of ac power in a 30-mph wind. The tower was 100 feet high, while the rotor measured 79 feet from tip to tip. This machine was particularly interesting in that, unlike conventional wind turbines, it used air rather than gears to transmit the propeller power to the generator. The propeller blades were hollow, and when they rotated, they acted as centrifugal air pumps. The air entered ports in the lower part of the tower, passed through an air turbine which turned the electric generator, went up through the tower, and went out the hollow tips of the blades. Unfortunately, friction losses in the internal air duct of the machine were large enough to minimize any advantages achieved by elimination of mechanical coupling.

The Danish also had a wind energy effort during the 1950's. The result of some of this work, the Danish Gedser wind turbine, is shown in figure 7. This machine, built in 1957, produced 200 kilowatts in a 33.6-mph wind. It was connected to the Danish public power system and produced approximately 400,000 kilowatt-hours per year. The tower was 85 feet high, and the rotor 79 feet in diameter. The generator was located in the housing on the top of the tower. The installation cost of this system was approximately $205 per kilowatt. This wind turbine ran until 1968, when it was stopped because the power produced was not cost competitive.

The French also did some wind energy work during the 1950's (refs. 7 and 12). They built at least two large machines. One machine (fig. 8), with an output of 130 kilowatts, had a blade diam-

Figure 7. - 200 kW Danish Gedser wind turbine.

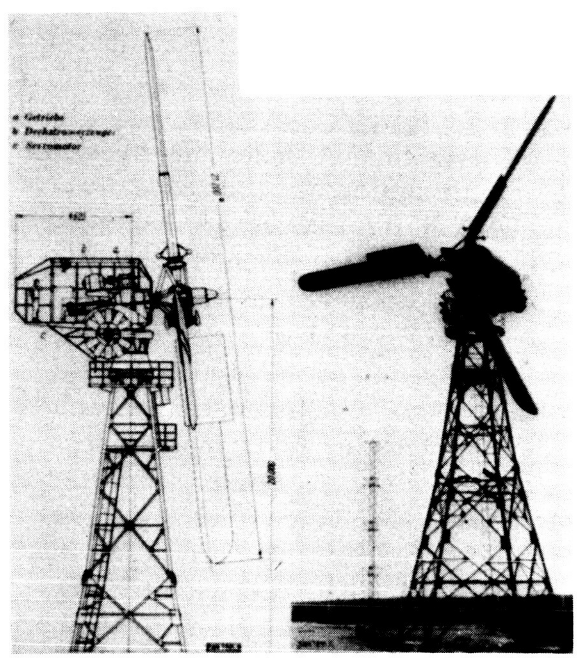

Figure 8. - 130 kW Electricite de France Neyrpic machine.

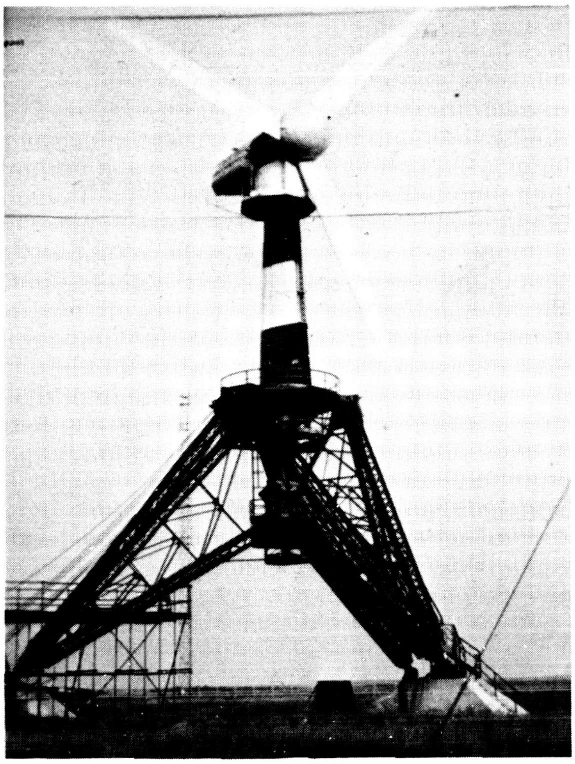

Figure 9. - 300 kW wind turbine located at Nogent Le Roi, France.

eter of approximately 70 feet; the other (fig. 9), with an output of 300 kilowatts, had a blade diameter of approximately 100 feet and was located at Nogent Le Roi.

The Germans, under the direction of Dr. Ulrich Hutter, did some very fine work in the 1950's and 1960's (ref. 7). The first machine, shown in figure 10, produced 100 kilowatts of power in an 18-mph wind. Previous machines required much higher wind speeds. This machine used lightweight 115-foot-diameter fiberglass blades and a simple hollow pipe tower supported by guy wires. The blade pitch could be changed at higher wind speeds to keep the propeller rotation constant. Dr. Hutter's machines ran from September 1957 to August 1968. During this period, he obtained more than 4000 hours of full rated power operation. He also made substantial contributions to the design of high-speed wind turbine rotors. The German effort constituted the most advanced work on large wind machines.

Although wind turbine systems have been built and tested in a number of countries around the world, these systems have been dismantled after running for a while. The problem has been that the installation cost per kilowatt has been too high when compared with those of other methods of producing electric power. In addition, because of wind

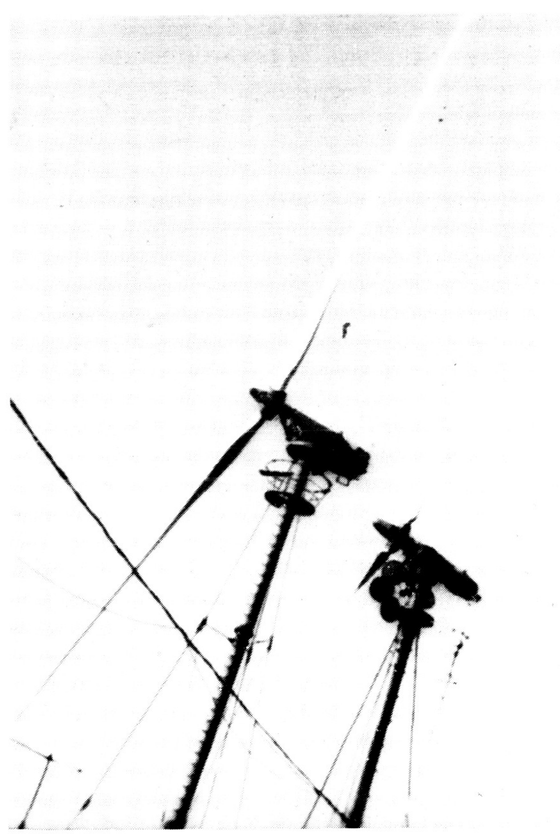

Figure 10. - 100 and 10 kW German (Ulrich Hutter) wind machines.

variability, it is usually not sufficient to have a wind turbine alone; some form of energy storage must also be considered.

Today's increasing cost of fuel coupled with potential fuel scarcities has caused the reexamination of wind energy as a future source of power. In this regard, the President and Congress have made the National Science Foundation (NSF), part of which has become the Energy Research and Development Administration (ERDA), responsible for carrying out the Nation's solar energy program, a part of which is wind energy.

Wind energy is being considered because

(1) It is nondepleting.
(2) It is nonpolluting.
(3) It uses free fuel.

These advantages must be weighed against the disadvantages:

(1) The wind is a variable source.
(2) System costs have been high.

The national wind energy part of the solar program (ref. 5) calls for

(1) Studies, construction, and testing of wind energy conversion systems with and without storage
(2) Studies, construction, and testing of energy storage systems
(3) Meteorological studies to estimate the wind energy in the Nation and to determine favorable regions and sites for wind-driven energy systems
(4) Studies and identification of suitable applications for wind energy demonstration tests

The planned accomplishments of this 5-year program are

(1) Identification of cost-effective wind energy conversion systems
(2) Construction and operation of prototypes of wind conversion systems
(3) Development and testing of components of wind conversion systems
(4) Identification of cost-effective energy storage systems
(5) Construction of demonstration systems with storage for selected applications
(6) An accurate estimate of the Nation's wind energy potential
(7) Developed techniques for selecting sites for wind conversion systems

The NASA-Lewis Research Center is managing the large-scale experiments project, that is, work on the 100-kilowatt and megawatt-size conversion systems. Lewis's participation is a direct result of our aeronautical and aerospace background. Many years of experience in aeronautics, propulsion, and space power systems research and development and project management give us a broad capability in all the required technologies. We also have from our large space projects the necessary systems experience.

The overall goal of the wind energy program is to expedite the development of reliable and cost-competitive wind energy conversion systems - systems which are capable of rapid commercial expansion to produce significant quantities of electrical energy as an alternative energy source. This Lewis 5-year wind energy project is a combined in-house and contractor effort consisting of

(1) The small systems project
(2) The megawatt-size systems project
(3) Supporting research and technology
(4) The energy storage project

The small systems project will develop cost-competitive wind energy conversion systems in the power range 50 to 250 kilowatts. The results of our early design and operating experience and the supporting research and technology effort will be used to provide input to the more advanced designs.

The first 100-kilowatt wind machine will be designed by Lewis using existing technology. It will be installed at our Plum Brook Station near Sandusky, Ohio, some 50 miles west of Cleveland. This machine, scheduled to be in operation in 1975, will provide early operational experience and will also serve as the test bed for testing cost-effective components resulting from the supporting research and technology project.

A 100-kilowatt wind energy system of advanced design will also be completed. This machine will be completed by contractor effort in two phases. In the first phase, contracts will be awarded for conceptual design, parametric analysis, and preliminary design. In the second phase, a contract will be awarded for detailed design, fabrication, erection, and operation of the most promising first-phase design. It is presently contemplated that two to four machines will be built and installed at selected sites. The succeeding program will depend on the results obtained from these experimental machines.

The megawatt-size systems project will develop wind energy conversion systems in the power range 500 to 3000 kilowatts for tie-in to existing public utility power lines.

The megawatt-size wind energy system will be based on existing technology and should have good inherent reliability. It will be designed and fabricated by contractor effort. This work, similar to the advanced work in the small systems project, will be done in two phases. In the first phase, contracts will be awarded for conceptual design, parametric analysis, and preliminary design of a high-power system. In the second phase, a contract will be awarded for the most promising first-phase design. The machine will be installed at a selected site to provide early operational experience with large systems. When operational experience and other technology inputs have been obtained, other experimental machines will be constructed for test installation at selected sites.

The supporting research and technology project will develop cost-effective components for both the small and megawatt-size advanced wind energy systems. The main work elements recognized at this time are various technology projects on blades, pitch change mechanisms, power transmission mechanisms, generators, controls, and energy storage systems.

The windmill test site at the Lewis Plum Brook Station is shown in figure 11. The photograph was taken at a

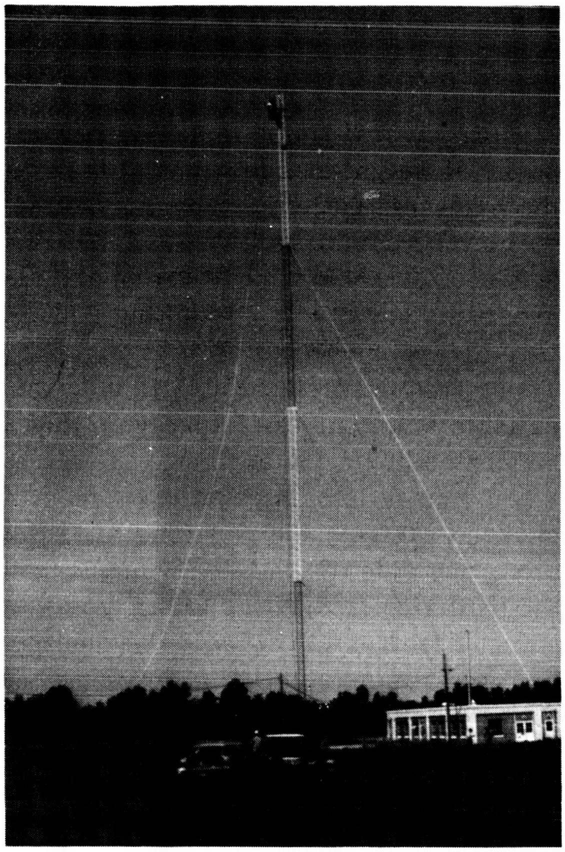

Figure 11. - Weather tower at Plum Brook site for 100 kW wind machine.

point southwest (upwind) of the windmill site looking northeast. (The prevailing summer wind is from the southwest.) The 200-foot instrumented weather tower shown in the figure will be used to obtain both steady flow and gust wind measurements. A small, 4.1-kilowatt, research windmill has been installed downstream and to the left of the weather tower. The 100-kilowatt windmill will be built some 600 feet downstream and to the right of the weather tower.

A simplified model of the 100-kilowatt machine is shown in figure 12. In the real machine, the truss tower will be 100 feet high and the rotor 125 feet in diameter (ref. 13). The machine will begin turning in an 8-mph wind and reach its rated output of 100 kilowatts in an 18-mph wind. The blade pitch will change to maintain a constant turning speed of 40 rpm and a constant output of 100 kilowatts at wind speeds greater than 18 mph.

Present plans are to shut the machine down at wind speeds lower than 8 mph or in excess of 60 mph. This wind turbine is similar to the design of Dr. Hutter. The main rotor is connected, through a gearbox, to an 1800-rpm 100-kilowatt generator. In the checkout phase of the system, the 480-volt three-phase 60-cycle synchronous generator will be connected to a load bank which is independent of the grid of the local utility company. After sufficient experience and confidence in

Figure 12. - Model of the NASA-Lewis 100 kW wind machine.

the wind machine are achieved, the generator will be connected to the local utility grid. The gearbox, generator, and control systems will all be located at the top of the tower.

In the past most windmills operated with the blades running ahead of the tower; the result was that the blades set up vibrations in the tower and caused it to fatigue. In our design the blades will run behind the tower, and the tower will set up vibrations in the blades. Since the blades will be flexible, they will be able to withstand these vibrations and provide the necessary long life.

The very important issues of storage and potential applications of the energy produced remain to be discussed. Some storage mechanisms are shown in figure 13. One storage mechanism is the battery. Typically, lead-acid batteries have an energy density of 10 watt-hours per pound, are good for about 1500 charge-discharge cycles, and cost $30 per kilowatt hour. At present no other conventional battery system can compete with the lead-acid battery for bulk energy storage (ref. 14). NASA and others are considering advanced battery systems potentially capable of storing several times more energy per pound of weight at a lower cost than can the lead-acid battery. These systems will not be commercially available in quantity for some time. There are also programs under way evaluating reduction-oxidation (redox) cells (ref. 15). These comprise electrodes immersed in suitable solutions of electrolytes that are separated by an ion exchange membrane. When energy is being extracted from the charged system, the reducing fluid flows along one side of the membrane, and the oxidizing fluid flows along the other side. Electrons flow from the electrode in the oxidizing solution to produce current flow in the external circuit, while ions are exchanged across the membrane to maintain the electric current and the chemical reaction. The system can be charged by flowing discharged fluids along the membrane while maintaining a suitable potential difference and current between the two fluids. The

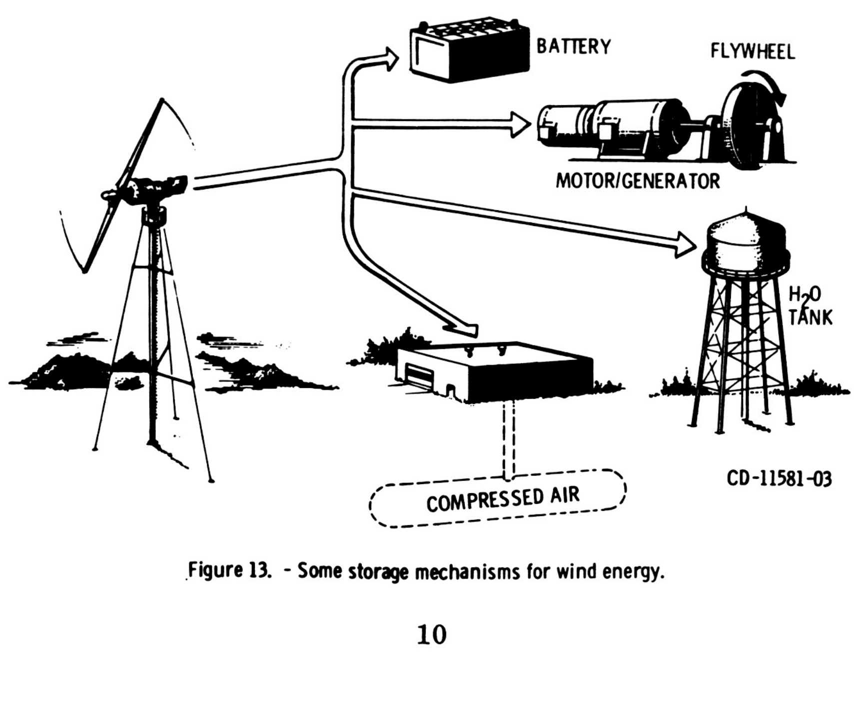

Figure 13. - Some storage mechanisms for wind energy.

advantage of this process is that the energy transfer and storage can be very efficient.

Work is also being done on high energy density flywheels (ref. 16). Researchers in the field feel that they may be able to double the energy storage per unit of weight compared to present lead-acid batteries. If suitable high efficiency mechanisms for the transfer of energy into and out of these flywheels are developed, they may become a competitive method of energy storage.

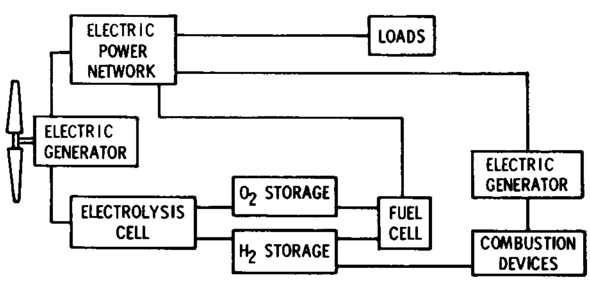

Figure 14. - Electrolysis of water for wind energy storage.

Other energy storage methods shown in figure 13 involve using wind energy to pump water into a tower or to compress air (refs. 17 and 18). The water or air would be used later to turn turbines and generate power.

Another wind energy storage technique receiving attention is shown in figure 14 (ref. 19). This technique uses wind-derived electric power to dissociate water into hydrogen (H_2) and oxygen (O_2) by electrolysis. The H_2 and O_2 can be piped to a site where electricity can be produced by fuel cells or H_2-O_2 combustion. The promise of this scheme lies basically in the low cost of transmitting the H_2-O_2 energy through pipelines.

One potential application of wind energy is the combining of a wind machine with an existing diesel electric system (fig. 15) (ref. 5). Preliminary economic analyses show that wind-generated electric power may now be competitive with diesel electric power in areas with high average wind velocities.

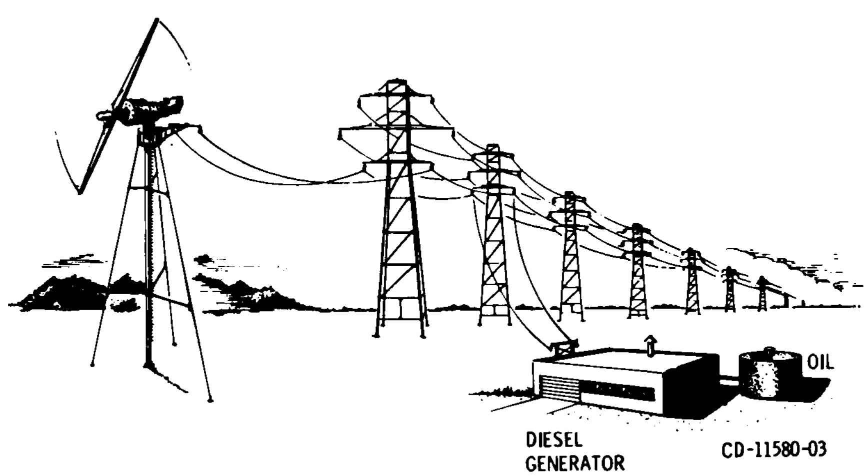

Figure 15. - Wind turbine integrated with existing diesel electric system.

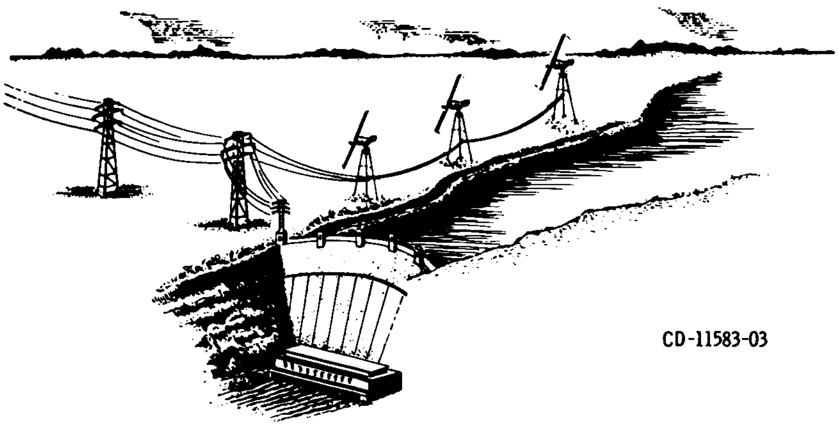

Figure 16. - Wind turbines integrated with an existing hydroelectric system.

Another potential application may be integration of a large wind energy system with a hydroelectric system. The arrangement shown in figure 16 might prove economical depending on a number of variables. A proposal (ref. 20) made by Professor Heronemus for a nationwide grid of windmills is illustrated in figure 17. The reasoning is that, although the winds are variable, on the average, there is always wind blowing in some areas. If a large number of windmills were spread over a large portion of our country and they were all interconnected, a large amount of power would be produced all the time. The concept, of course, has yet to be verified in a practical sense.

In conclusion, the wind contains a large amount of available energy. Recognizing this, several countries have built and tested wind machines. These machines have shown the technical feasibility of wind generators, but the fol-

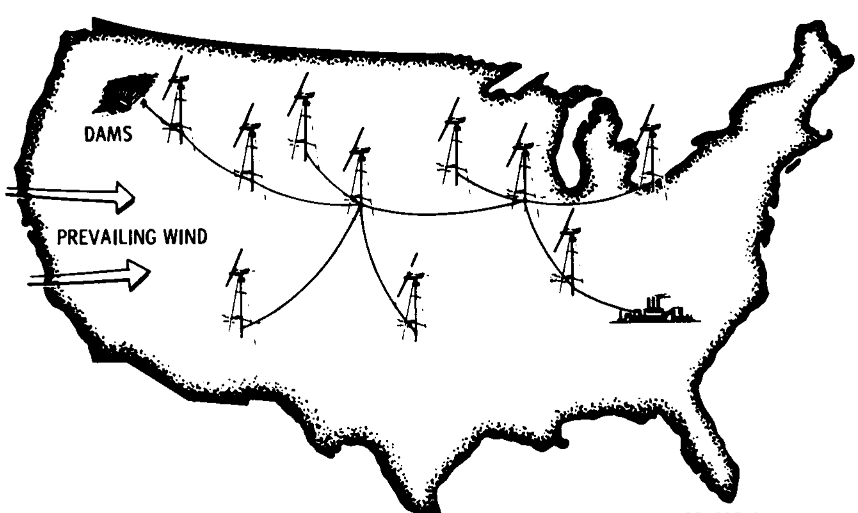

Figure 17. - Wind turbines distributed to take advantage of prevailing winds.

lowing problems have yet to be solved:

(1) Energy storage systems are required because winds are variable.

(2) Installation and hence operating costs are high when compared with those of fossil fuel systems.

(3) A major sustained effort is needed to make wind machines competitive with other energy producing systems.

Because of today's energy problems, NASA is cooperating with ERDA, formerly NSF, in a 5-year wind energy program. The objective of this program is to develop cost-competitive wind energy systems. Preliminary analyses show that in the high average wind areas wind-generated energy can be competitive with some other existing power production methods.

Using present technology, the NASA Lewis Research Center will install and operate a 100-kilowatt windmill at the Plum Brook Station during 1975. This machine will be a precursor of future larger machines.

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